Appendix G.
Determination of Critical Conditions for the Chesapeake Bay TMDL

Introduction

The Chesapeake Bay TMDL must be developed to attain applicable water quality standards. Critical conditions for stream flow pollutant loading and water quality parameters must be taken into account. All approvable TMDLs must be established in a manner that reflects *Critical Conditions*. Critical conditions are represented by the combination of loading, waterbody conditions, and other environmental conditions that result in impairment and violation of water quality standards. Critical conditions for an individual TMDL typically depend on applicable water quality standards, characteristics of the observed impairments, source type and behavior, pollutant, and waterbody type. In establishing the Chesapeake Bay TMDL, it was necessary to define a *Critical Period*, a period during which hydrologic, temperature, environmental, flow, and other such conditions result in a waterbody experiencing critical conditions with respect to an identified impairment (e.g., summer low flow, winter high flow). The approach chosen in the Chesapeake Bay TMDL was to select a 3-year period as the critical period.

The Chesapeake Bay Program's Water Quality Goal Implementation Team decided that the critical period would be selected from the previously selected hydrologic period 1991–2000 because that time frame is representative of long-term hydrology, is within the model calibration period, and would facilitate modeling operations (see Sections 6.2.1 and 6.5.1 and Appendix F). A 3-year period was selected to coincide with the Chesapeake Bay water quality criteria assessment period (USEPA 2003).

The Water Quality Goal Implementation Team also agreed that the critical period should be representative of an approximate 10-year return period. The return period is defined as the average period of time expected to elapse between occurrences of events at a certain site. A 10-year event is an event of such size that over a long period, the average time between events of equal or greater magnitude is 10 years. The team believed that 10 years was a good balance between guarding against extreme events (greater than 10-year return frequency) and ensuring attainment during more frequent critical events (occurring within less than a 10-year period). The selection of a 10-year return period was also based on the commonly applied 10-year return period for application of the 7Q10 low flow conditions. Finally, the 10-year return period is also consistent with the critical periods selected for other TMDLs developed and published by the Chesapeake Bay watershed jurisdictions.

The following sections discuss the process for determining the critical period on the basis of determining the return period for each of the 3-year time frames within the selected 1991–2000 hydrologic period using various methods. A critical period was selected for assessing achievement of the jurisdictions' Chesapeake Bay dissolved oxygen (DO) and water clarity/submerged aquatic vegetation (SAV) water quality standards. As described below, there was no basis for selecting a specific 3-year critical period for assessment of achievement of the jurisdictions' numerical chlorophyll *a* water quality standard.

Approaches Used in Previous TMDLs to Select the Critical Period

To determine if there is a consistent approach to establishing a critical period among the Chesapeake Bay watershed jurisdictions, each jurisdiction's water quality standards were reviewed, the seven watershed jurisdictions were polled, and previously completed TMDLs were referenced.

Generally, the jurisdictions' water quality standards do not address a method for establishing the critical hydrologic period. Further, EPA does not have specific guidance or regulations on how to determine critical period. EPA only requires that critical conditions and seasonal variations are considered [40 CFR 130.7(c)(1)]. EPA Region 3 has not required any specific method for determining critical conditions and seasonal variations as long as the critical condition captures the *worst case* scenario or the most vulnerable environmental conditions in the waterbody in which the loading expressed in the TMDL for the pollutant of concern will continue to meet water quality standards.

In polling the jurisdictions regarding their approaches to determining the hydrology critical period, all jurisdictions reported that the determination is dependent on the pollutant, the water quality standards, the TMDL endpoint, and the amount of flow data available. All jurisdictions reported that the critical period was determined using a representative data set capturing a range of high, low, and average flows. Maryland, the District of Columbia, and Virginia reported selecting the critical period by using a dry year, an average year, and a wet year. Maryland also indicated that in some TMDLs, time-variable models use the worst condition in the calibration period. Although, nutrient TMDLs with steady-state models use 7Q10 flows as the critical period. Delaware reported using the 7Q10 for free-flowing streams and using the monthly or seasonally average as the critical condition for the calibration period for tidal streams. Pennsylvania reported recently beginning to use the growing season average as the critical period for nutrient TMDLs. West Virginia watershed TMDLs use representative precipitation-induced flow data over a 6-year period with high, low, and average conditions.

A review of TMDLs completed for tidal influenced streams and estuaries along the Atlantic and Gulf Coasts revealed that there is no consistent method for determining the critical period. That review was not intended to be exhaustive but to reveal general patterns of methodology across the country. Most TMDLs used a critical period that was protective during low flows, rather than high flows, the condition of interest for the Chesapeake Bay TMDL.

The most commonly identified method for establishing the critical period was the use of 7Q10 flows. The *Louisiana Standard Operating Procedures for Louisiana TMDL Technical Procedures* (LDEQ 2009) specifically outlines the summer critical conditions as 7Q10 or 0.1 cubic feet per second (cfs), whichever is greater, or for tidal streams one-third of the average or typical flow averaged over one tidal cycle. Similarly, winter critical conditions are 7Q10 of 1 cfs, whichever is greater, or for tidal streams one-third of the average or typical flow averaged over one tidal cycle.

Other examples of using 7Q10 flows include the following:

- **Total Maximum Daily Load Analysis for Nanticoke River and Broad Creek, Delaware (DNREC 1998).** The model for this DO, total nitrogen, and total phosphorus TMDL was developed and calibrated using hydrologic and hydrodynamic from 1992, a dry

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year. Hydrodynamic Model was run using 7Q10 flows, water quality model was run using 1992 pollutant loads.

- **Organic Enrichment/Dissolved Oxygen TMDL Rabbit Creek and Dog River, Alabama (ADEM 2005).** The hydrology of the LSPC model was calibrated for the period of record, October 1, 1996, through September 30, 2000. For the purposes of this TMDL the 2000-year was used as the critical low-flow period. 2000 was a relatively dry year and was one of the periods over which the models were calibrated, lending confidence to the simulations. The period of the model simulation was from 2000 to 2001. This period was selected on the basis of the availability and relevance of the observed data to the current conditions in the watershed. The model was calibrated for the year 2000, which represented both high- and low-flow periods. In 2000 flows were very low and near critical 7Q10 conditions, while in 2001 flows were higher.

- **TMDL Bayou Sara/Norton Creek – Mobile River Basin Organic Enrichment/DO (ADEM 1996).** Summer (May–November) TMDL critical conditions and MOS were established as 7Q10 flows and 30 degrees Celsius (°C). The winter (December–April) TMDL critical conditions and MOS were established as 7Q2 and 20 °C.

- **Total Maximum Daily Load Cooper River, Wando River, Charleston Harbor System, South Carolina (SCDHEC 2002).** Critical conditions for this DO TMDL were determined in the model by setting water quality parameters to represent 75/25 percentiles. The average spring and neap tidal conditions were evaluated with freshwater inflow set to approximate a 7Q10 recurrence, and algal processes were turned off. The model was calibrated to a 3-day period and validated on a 2-day period in 1993. The seasonal critical period was considered to be the low-flow, high-temperature conditions associated with summer and early fall.

- **Total Maximum Daily Load Ashley River, South Carolina (SCDEHC 2003).** The recommended critical flow period includes setting uncontrolled freshwater inflows to 7Q10 flows and selecting the seaward tidal boundary to represent a full lunar month including both spring and neap tides. Those conditions approach worst-case conditions for the impact of point sources on river DO levels. The wasteloads determined for the critical conditions are considered to be protective of the river DO standard when river flow is equal to or greater than 7Q10 because higher flows would provide greater dilution. Higher river flows are expected during wet weather, so the wasteloads should be protective under those conditions.

Another common method for determining the critical period was selecting a 3-year time span on the basis of precipitation, selected to include a wet year, a dry year, and a normal year. Some examples of this approach include the following:

- **Total Maximum Daily Load Analysis for Indian River, Indian River Bay and Rehoboth Bay, Delaware (DNREC 1998).** This is a nitrogen and phosphorus TMDL. The baseline period was established as 1988 through 1990. The hydrologic condition of the year 1988 was considered to represent a dry year, 1989 a wet year, and 1990 a normal year. No indication of the full data set from which the baseline period was established was given.

- **Total Maximum Daily Loads of Nitrogen and Phosphorus for Baltimore Harbor in Anne Arundel, Baltimore, Carroll, and Howard Counties and Baltimore City, Maryland (MDE 2006).** The baseline conditions scenario represents the observed

conditions of the Harbor and its tributaries 1995–1997. Simulating the system for 3 years accounts for various loading and hydrologic conditions, which represent possible critical conditions and seasonal variations of the system. For example, the 1995–1997 period includes an average year (1995), a wet year (1996) and a dry year (1997).

- **Total Maximum Daily Load Organic Enrichment/Dissolved Oxygen Threemile Creek, Alabama (ADEM 2006).** The hydrology of the LSPC model was calibrated for the period of record, October 1, 1996, through September 30, 2000. The period of the model simulation was from 2000 to 2001. That period was selected on the basis of the availability and relevance of the observed data to the current conditions in the watershed. The model was calibrated for the year 2000, which represented both high and low-flow periods. The model was simulated from May 2000 through April 2001 to account for both summer (May–November) and winter (December–April) conditions. In the natural conditions model, two critical periods were selected to establish seasonal TMDLs. A period during June 2000 was simulated under natural conditions, which resulted in a minimum DO concentration of 1.91 milligrams per liter (mg/L) at a 5-foot depth. That June event defines critical conditions in Threemile Creek during the summer season. A period during April of 2001, the model simulated natural condition is 2.26 mg/L at a 5-foot depth and defines the winter critical period. A low-flow period with high temperatures for both summer and winter seasons was used to represent the worst-case conditions.

- **Total Maximum Daily Loads of Nutrients/Biochemical Oxygen Demand for the Anacostia River Basin, Montgomery and Prince George's Counties, Maryland and the District of Columbia. (MDE and DC DOE 2008).** The critical condition and seasonality was accounted for in the TMDL analysis by the choice of simulation period, 1995–1997. That 3-year period represents a relatively dry year (1995), a wet year (1996), and an average year (1997), based on precipitation data, and accounts for various hydrological conditions including the critical condition.

Two TMDLs used the period of the worst hypoxia as the critical period. DO exceedances for Long Island Sound were dominated by point sources. Further details regarding the TMDLs follow:

- **A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound (NYSDEC and CTDEP 2000).** Annual surveys from 1986 to 1998 and a review of historical data indicated that the 1988–1989 modeling time frame was the most severe period of hypoxia on record. As a result, model simulations of reduced nitrogen inputs were used to predict water quality conditions that would result during the same physical conditions that exist during the 1988–1989 period. The use of 1988–1989 worst-case scenario was considered an implicit margin of safety.

- **Total Maximum Daily Load for Nitrogen in the Peconic Estuary Program Study Area Including Waterbodies Currently Impaired Due to Low Dissolved Oxygen: the Lower Peconic River and Tidal Tributaries; Western Flanders Bay and Lower Sawmill Creek; and Meetinghouse Creek, Terrys Creek and Tributaries (Peconic Estuary Program 2007).** The Environmental Fluid Dynamics Code (EFDC) model was calibrated using an 8-year period from October 1, 1988, to September 30, 1996 and validated using the 6-year period from October 1, 196, through September 30, 2002. Model calibration and verification included all seasons of the year, as well as extreme wet and dry years.

Monitoring data indicated that the October 2000 to September 2002 time frame was the most severe period of hypoxia on record from 1988 to 2002. October 1, 2000, to September 30, 2002, was selected as the critical period for the TMDL model runs.

In some cases, the data set either does not contain a critical year or several years are included to capture a range of temperature and flow concentrations. The *TMDLs for The Little Assawoman Bay and Tributaries and Ponds of the Indian River, Indian River Bay, and Rehoboth Bay* (DNREC 2004) is an example of the former. There was no *worst* year for DO, nitrogen and phosphorus during the 3-year period in question, so the average over the three summers was used as the critical (design) condition. The *TMDL for Nutrients in the Lower Charles River Basin, Massachusetts* (MassDEP and USEPA 2007) is an example of the latter. A continuous, 5-year simulation was run. The 1998–2002 period was selected because it represented some of the lowest summer flows throughout the 23-year period of record. Low flows at or near the 7Q10 flow value were observed during three of the summers during the selected critical period.

Two of the TMDLs reviewed had limited data sets, so the critical period was chosen on the basis of the period with the most data available. Examples of this approach follow:

- **Total Maximum Daily Loads of Nitrogen and Phosphorus for the Upper and Middle Chester River, Kent and Queen Anne's Counties, Maryland (MDE 2006).** The models were calibrated to the period of 1997–1999, which was the most recent period for which all of the needed data were available and consistent with the Chesapeake Bay Program modeling efforts of the Tributary Strategies. Only the output from 1997 was used to investigate different nutrient loading scenarios and calculate the annual average and growing season TMDLs for the Upper and Middle Chester rivers because in 1999, the region experienced extreme weather conditions (prolonged drought followed by Hurricane Floyd) resulting in atypically high flows and loads. On the basis of the flow gauge, it was determined that the flow in 1997 was representative of the average annual flow and loads. The timeframe selected includes representative wet and dry periods, accounting for seasonality and critical conditions.

- **Total Maximum Daily Load for Dissolved Oxygen in Mill Creek, Northampton County, Virginia (VADEQ 2009).** The observations show that the instantaneous DO levels fell below the water quality criterion of 4 mg/L minimum repeatedly throughout the period of 1997–2003. Because the nutrients data in the watershed were not available, an interactive approach of calibration of watershed and in-stream water quality model was conducted using all available in-stream monitoring data. The water quality model was calibrated in Mill Creek using the observation data. A 6-year model simulation (1998–2003) was conducted. Seasonal variations involved changes in surface runoff, stream flow, and water quality condition as a result of hydrologic and climatologic patterns. Those were accounted for by using this long-term simulation to estimate the current load and reduction targets.

Initial Analysis by Malcolm Pirnie

The consulting firm Malcolm Pirnie, representing the stakeholders from the Maryland Association of Municipal Wastewater Agencies, Inc. (MAMWA) and the Virginia Association of Municipal Wastewater Agencies, Inc. (VAMWA) conducted an independent analysis of the

inflows to the Chesapeake Bay to determine whether the initially selected critical period of 1996–1998 might represent a hydrologic condition with a longer return period than 10 years (Malcolm Pirnie 2009).

Malcolm Pirnie analyzed the flows from the Potomac and Susquehanna rivers, which together contribute most of the flow to the Chesapeake Bay, for the period 1967 through 2009. The average daily inflow from January through May was calculated for each year and for each 3-year period within the 42-year period of record. January through May was selected as the period of interest because studies have indicated that the magnitude and extent of hypoxia in the Chesapeake Bay is largely controlled by freshwater and nutrient inputs during the preceding winter and spring months (freshet).

Results indicated that 1996–1998 had the highest average January through May inflow over the entire period of record and would result in a return period of 40 years. The year 1996 had January through May inflows in the 93rd percentile and 1998 had flows in the 98th percentile. High flows in 1996 were attributed to rainfall on winter snowpack in January 1996, resulting in an event know as the *Big Melt*.

On the basis of those results, Malcolm Pirnie indicated that the critical condition would be too extreme if 1996–1998 were selected as the critical period. Malcolm Pirnie recommended using 1993–1995 or 1994–1996 as the critical period because they represent return flows much closer to a 10-year return period.

Replication of Malcolm Pirnie Results

To confirm the results of the Malcolm Pirnie analysis, Tetra Tech staff replicated the approach used in the Malcolm Pirnie flow analysis. The analysis was repeated using both the flow data presented in the Malcolm Pirnie technical memo (Malcolm Pirnie 2009) and the raw flow data from the U.S. Geological Survey (USGS). Although the replicated 3-year averages based on the flows in the technical memo did not match exactly what was presented in the technical memo, the minor discrepancies did not affect the percentile calculations. Similarly, the 3-year running averages using the raw USGS data resulted in minor discrepancies from the Malcolm Pirnie results. Despite the small differences, Tetra Tech's replication yielded the same results as the Malcolm Pirnie technical memo (Malcolm Pirnie 2009).

Analysis to Support Critical Period Selection

Additional analyses were performed to further explore the options for the selection of the critical period.

Preliminary analysis included an exploration of the results of including the nine major rivers in the flow analysis and expanding the combinations of different monthly flow durations beyond January to May to include other monthly duration combinations from September through July. Data were analyzed for 1978 through 2009 because the Patuxent flow gage did not begin until 1977. Refer to Table G-1 for the gages used in the analysis and the period for which data was available. Running 3-year average flows were calculated for 25 different month combinations for the entire period of evaluation. The probability of each 3-year flow average was determined

using the Weibull Plotting Position. The return period is the inverse of the probability. That method differed from the approach in the Malcolm Pirnie analysis (Malcolm Pirnie 2009), which used percentile ranks. A regression was also performed on the 3-year flow averages to determine if there was a correlation with the DO percent exceedances. The percent DO exceedances were provided by EPA's Chesapeake Bay Program Office (CBPO) and represent volume exceedances. The analysis was run with and without the use of tributary multipliers, which the CBPO developed because flows from different tributaries do not affect conditions in the Bay equally. Those factors are the estuarine delivery factors presented in the Section 6.3.1. The CBPO multipliers were translated to a 0.0 to 1.0 scale and are included in Table G-2. Without the multipliers, the Susquehanna and Potomac rivers contribute approximately 80 percent of the flow to the Bay. With the multipliers, the two rivers contribute approximately 95 percent of the effective load.

Table G-1. Flow gages and period of available data

Gage ID	Description	Start	End
1668000	Rappahannock River near Fredericksburg, VA	9/19/1907	8/25/2009
1646502	Potomac River (Adjusted) near Washington, DC	3/1/1930	7/31/2009
2037500	James River near Richmond, VA	10/1/1934	8/25/2009
1674500	Mattaponi River near Beulahville, VA	9/19/1941	8/25/2009
1673000	Pamunkey River near Hanover, VA	10/1/1941	8/25/2009
1491000	Choptank River near Greensboro, MD	1/1/1948	8/25/2009
1578310	Susquehanna River at Conowingo, MD	10/1/1967	8/25/2009
2041650	Appomattox River at Matoaca, VA	10/1/1969	8/25/2009
1594440	Patuxent River near Bowie, MD	6/27/1977	8/25/2009

Table G-2. Chesapeake Bay tributaries flow multiplier ratios

Major river basin	Multiplier	Adjusted ratio
Appomattox	0.533111028	0.017
Choptank	6.929861533	0.217
James	0.533111028	0.017
Mattaponi	0.798423188	0.025
Pamunkey	0.798423188	0.025
Patuxent	3.093385849	0.097
Potomac	6.188243619	0.193
Rappahannock	2.809613056	0.088
Susquehanna	10.3187158	0.322
		1.000

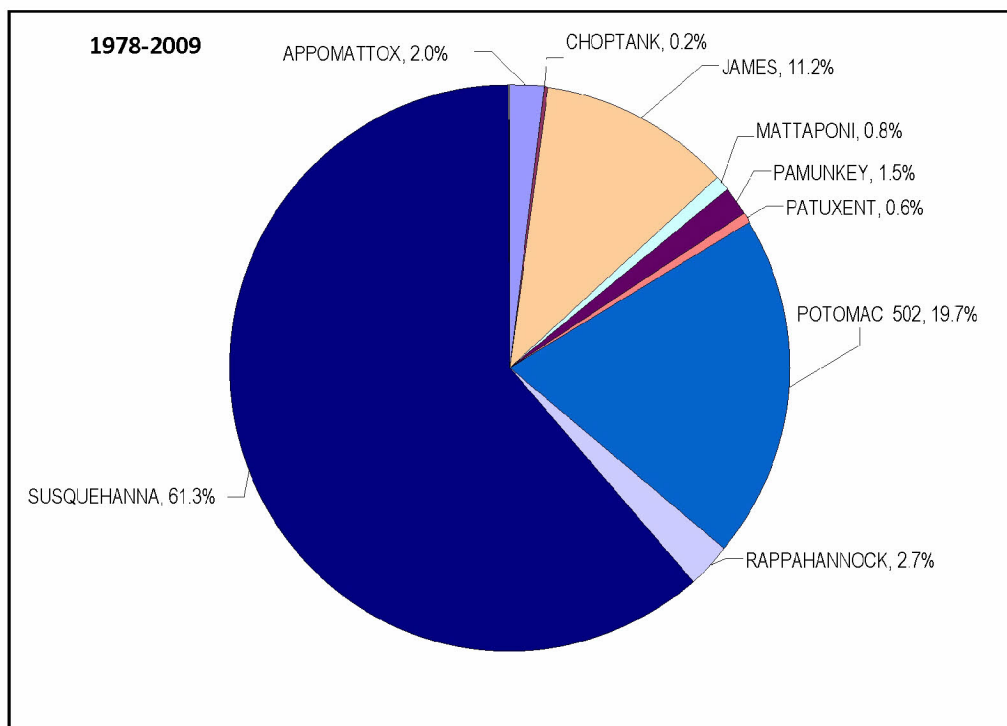Source: EPA Chesapeake Bay Program Office

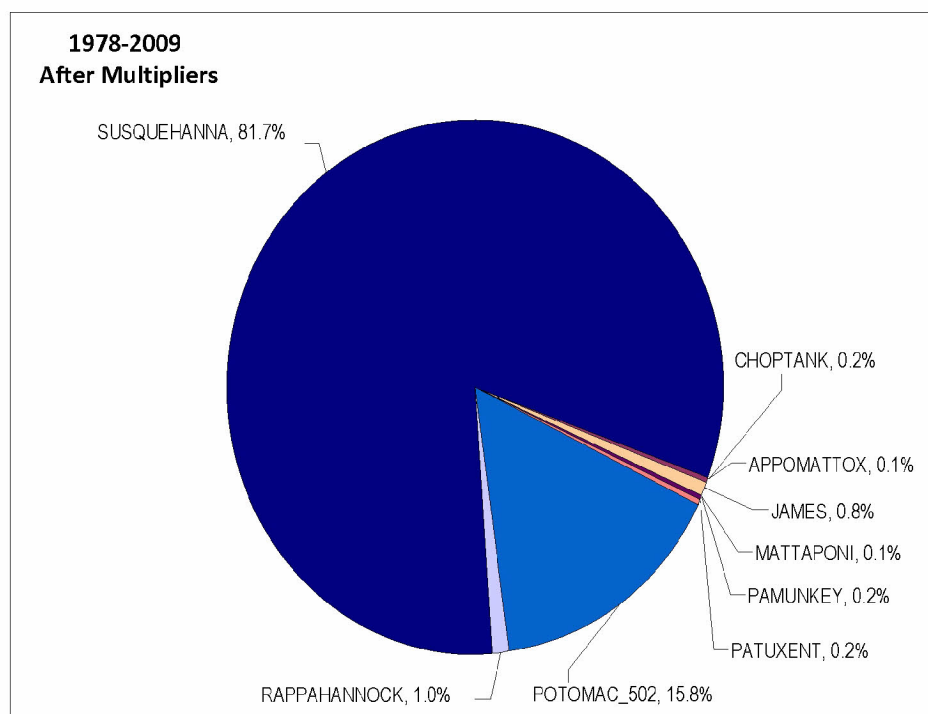**Figure G-1. Tributary flow contributions without multiplier ratios.**

Figure G-2. Tributary flow contributions with the multiplier ratios.

Results of the analysis, as shown in Tables G-3 and G-4, indicate that the monthly span should be extended beyond the January through May period suggested in the Malcolm Pirnie analysis (Malcolm Pirnie 2009) because the 3-year flow averages with the highest correlation to DO exceedances generally included longer monthly spans. The 3-year average flow with the highest correlation to DO exceedances was September through June. Findings also suggest that 1996–1998 had closer to a 15-year return period for months when flow was more closely correlated with DO exceedances. The other possible critical periods 1992–1994 and 1993–1995 had generally lower than 10-year return periods and return periods greater than 10 years when flow was not strongly correlated with DO exceedances. Return periods greater than 6 years are highlighted in Tables G-3 and G-4, and only 3-year average flows with at least one monthly interval with a 6-year or greater return period are shown. There were no 3-year average flows with return periods greater than 6 years for any of the years between 1978 and 1991.

Table G-3. Return periods and R^2 correlation between various monthly durations and DO percent exceedances without the Tributary Multiplier Ratio.

% DO Exceedences --->		25.87%	25.92%	24.26%	27.84%	26.05%	31.11%	27.24%
Interval	R2	1992-1994	1993-1995	1994-1996	1996-1998	1997-1999	2003-2005	2004-2006
					Return Period			
SEP-JUNE	0.54	4.43	6.20	3.44	15.50	2.58	31.00	7.75
NOV-JUNE	0.53	6.20	7.75	5.17	31.00	2.07	15.50	4.43
SEP-JULY	0.53	4.43	5.17	3.44	15.50	2.58	31.00	10.33
NOV-JULY	0.52	6.20	7.75	4.43	15.50	2.07	31.00	5.17
DEC-JUNE	0.52	7.75	6.20	4.43	31.00	2.38	15.50	3.88
SEP-MAY	0.51	4.43	6.20	3.88	15.50	3.10	31.00	7.75
DEC-JULY	0.51	6.20	7.75	4.43	31.00	2.21	15.50	3.88
OCT-JUNE	0.50	5.17	6.20	4.43	15.50	2.38	31.00	7.75
OCT-JULY	0.49	5.17	6.20	4.43	15.50	2.21	31.00	7.75
NOV-MAY	0.48	6.20	7.75	5.17	31.00	3.10	15.50	4.43
SEP-APR	0.48	4.43	5.17	3.44	15.50	3.10	31.00	10.33
OCT-MAY	0.46	5.17	7.75	4.43	31.00	2.82	10.33	6.20
DEC-MAY	0.46	10.33	7.75	5.17	31.00	2.82	6.20	3.88
JAN-JUNE	0.44	10.33	6.20	4.43	31.00	2.58	5.17	2.21
JAN-JULY	0.44	6.20	5.17	4.43	31.00	2.21	7.75	2.82
NOV-APR	0.44	7.75	10.33	4.43	31.00	3.10	15.50	5.17
OCT-APR	0.42	5.17	7.75	3.44	31.00	3.10	15.50	6.20
SEP-MAR	0.42	2.82	3.44	3.88	15.50	4.43	31.00	10.33
DEC-APR	0.40	10.33	15.50	5.17	31.00	3.10	6.20	4.43
NOV-MAR	0.39	3.10	3.44	6.20	31.00	4.43	15.50	7.75
JAN-MAY	0.37	10.33	7.75	6.20	31.00	3.10	4.43	2.21
OCT-MAR	0.36	2.82	3.44	4.43	31.00	3.88	10.33	7.75
DEC-MAR	0.36	3.44	5.17	7.75	31.00	4.43	10.33	6.20
JAN-APR	0.32	31.00	15.50	6.20	10.33	3.44	3.88	2.38
JAN-MAR	0.26	5.17	6.20	10.33	31.00	7.75	3.88	2.58

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Table G-4. Return periods and R^2 correlation between various monthly durations and DO percent exceedances with the Tributary Multiplier Ratio

% DO Exceedences --->		25.87%	25.92%	24.26%	27.84%	26.05%	31.11%	27.24%
Interval	R2	1992-1994	1993-1995	1994-1996	1996-1998	1997-1999	2003-2005	2004-2006
					Return Period			
SEP-JUNE	0.53	4.43	5.17	3.44	7.75	2.21	31.00	15.50
NOV-JUNE	0.53	5.17	6.20	4.43	15.50	1.94	31.00	7.75
DEC-JUNE	0.52	6.20	7.75	3.88	15.50	1.94	31.00	4.43
SEP-JULY	0.52	3.88	5.17	3.44	10.33	2.07	31.00	15.50
NOV-JULY	0.52	5.17	6.20	4.43	15.50	1.94	31.00	10.33
DEC-JULY	0.51	5.17	6.20	3.88	15.50	1.94	31.00	7.75
OCT-JUNE	0.49	5.17	6.20	3.88	15.50	2.07	31.00	7.75
SEP-MAY	0.49	4.43	5.17	3.88	7.75	2.58	31.00	15.50
OCT-JULY	0.48	5.17	6.20	3.88	15.50	1.94	31.00	10.33
NOV-MAY	0.46	6.20	7.75	4.43	31.00	2.38	15.50	5.17
SEP-APR	0.46	4.43	5.17	3.44	6.20	2.82	31.00	15.50
JAN-JULY	0.46	10.33	5.17	4.43	31.00	1.55	15.50	3.88
JAN-JUNE	0.46	10.33	6.20	4.43	31.00	1.82	5.17	2.82
DEC-MAY	0.45	7.75	10.33	5.17	31.00	2.21	6.20	4.43
OCT-MAY	0.44	5.17	6.20	3.88	15.50	2.21	10.33	7.75
NOV-APR	0.42	7.75	10.33	3.88	15.50	2.58	31.00	6.20
SEP-MAR	0.41	2.07	3.10	3.88	10.33	4.43	15.50	31.00
OCT-APR	0.41	5.17	6.20	3.44	10.33	2.58	31.00	7.75
DEC-APR	0.40	15.50	31.00	4.43	10.33	2.58	7.75	5.17
NOV-MAR	0.38	2.58	3.10	5.17	31.00	3.44	15.50	10.33
JAN-MAY	0.37	15.50	7.75	6.20	31.00	2.38	5.17	2.82
DEC-MAR	0.37	2.58	3.44	6.20	31.00	3.88	15.50	10.33
OCT-MAR	0.35	2.38	3.10	4.43	31.00	3.44	10.33	15.50
JAN-APR	0.32	31.00	15.50	6.20	10.33	2.58	5.17	3.44
JAN-MAR	0.28	2.58	3.88	10.33	31.00	7.75	6.20	2.82

Analysis of Critical Period Using the Log Pearson III Method

After determining the return period using the Weibull Plotting Position method, a second method, the Log Pearson III Method (U.S. Interagency Advisory Committee on Water Data 1982; Ponce 1989), was used to determine whether the return period changed significantly depending on the method of calculation. The Log Pearson III method provides a smooth fit through the plotting position data and in essence smoothens out the predicted values. That analysis was conducted over the same 1978 through 2009 period and focused on monthly spans with the highest correlation between flow and DO exceedances. Results in Table G-5 and Table G-6 show that there are some changes in the return periods, but the conclusion in terms of candidate years remains the same. This method of determining the return period was used in subsequent analyses.

Table G-5. Log Pearson III method for determining return period, without Tributary Multiplier Ratio.
Without Multiplier

% DO Exceedences	25.87%	25.92%	24.26%	27.84%	31.11%	27.24%
Year	1992-1994	1993-1995	1994-1996	1996-1998	2003-2005	2004-2006
Sep-June	4.38	4.90	3.77	17.99	34.80	12.37
Nov-June	7.45	7.90	5.46	20.71	19.09	5.36
Sep-July	4.16	4.79	4.05	16.77	36.03	14.15
Nov-July	6.79	7.53	6.02	18.95	20.33	6.59
Dec-June	9.19	9.11	6.68	19.70	15.89	4.24
Sep-May	4.90	5.74	3.80	17.77	23.83	11.69
Dec-July	8.39	8.66	7.26	18.14	17.24	4.97
Oct-June	5.44	6.15	4.60	19.99	21.57	7.16
Flow (Sep-June) (cfs)	81,791	83,254	80,099	95,684	101,516	92,106
Flow (Nov-June) (cfs)	97,725	98,368	94,810	108,161	107,300	94,664
Flow (Sep-July) (cfs)	76,755	78,432	76,487	89,677	96,200	88,110
Flow (Nov-July) (cfs)	89,756	90,753	88,724	99,399	100,142	89,485
Flow (Dec-June) (cfs)	104,233	104,117	100,461	111,988	109,418	95,653
Flow (Sep-May) (cfs)	86,706	88,203	83,278	100,501	103,783	96,146
Flow (Dec-July) (cfs)	94,451	94,829	92,906	101,658	101,107	89,709
Flow (Oct-June) (cfs)	88,780	89,746	87,057	101,106	101,688	91,140

Table G-6. Log Pearson III method for determining return period, with Tributary Multiplier Ratio.
With Multiplier

% DO Exceedences	25.87%	25.92%	24.26%	27.84%	31.11%	27.24%
Year	1992-1994	1993-1995	1994-1996	1996-1998	2003-2005	2004-2006
Sep-June	4.39	5.17	3.87	13.21	35.52	18.76
Nov-June	7.47	8.19	5.70	16.84	19.21	8.52
Sep-July	4.19	4.83	4.04	12.21	36.18	21.53
Nov-July	6.85	7.48	5.98	16.06	21.37	10.34
Dec-June	9.17	9.27	6.76	16.02	17.64	6.88
Sep-May	4.92	6.32	4.08	13.12	24.42	17.15
Dec-July	8.38	8.39	7.08	14.58	18.76	8.73
Oct-June	5.40	6.41	4.67	16.09	22.11	10.74
Flow (Sep-June) (cfs)	19,682	20,141	19,338	22,251	24,445	23,100
Flow (Nov-June) (cfs)	23,429	23,668	22,837	25,294	25,648	23,779
Flow (Sep-July) (cfs)	18,494	18,892	18,400	20,891	23,136	22,147
Flow (Nov-July) (cfs)	21,550	21,739	21,292	23,285	23,910	22,535
Flow (Dec-June) (cfs)	24,860	24,893	24,069	26,006	26,242	24,110
Flow (Sep-May) (cfs)	20,897	21,462	20,265	23,415	25,103	24,122
Flow (Dec-July) (cfs)	22,568	22,569	22,178	23,659	24,214	22,671
Flow (Oct-June) (cfs)	21,337	21,662	20,998	23,689	24,436	22,921

Analysis of Critical Period Using Expanded Flow Data

Given some concern that the 30-year period from 1978 through 2009 was of insufficient length to fully capture the return period over the full period of flow data and was artificially lowering the most extreme return period to 30 years, an extended analysis was performed for the years 1930 through 2009 but only included the Potomac and Susquehanna rivers. The Potomac and Susquehanna rivers account for almost 80 percent of the total flow to the Chesapeake Bay, and if the CBPO allocation multipliers are used, those two rivers account for almost 95 percent of the total inflow to the Chesapeake Bay. Hence, those two flow gages were considered sufficient for analysis purposes. The two USGS flow gages are described in Table G-1.

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The Susquehanna River at Conowingo gage flow data runs from October 1, 1967, to the present. The period before October 1, 1967, was patched using data from the Susquehanna River at Harrisburg gage (01570500 – October 1, 1890, to August 25, 2009) using a simple drainage area ratio method. The daily freshwater inflow from the Potomac and Susquehanna rivers were weighed using the adjusted tributary multipliers provided by the CBPO (Table G-7).

Table G-7. Adjusted tributary flow multiplier ratios

Gage	Multiplier	Adjusted ratio
Potomac	6.188	0.375
Susquehanna	10.317	0.625

Source: EPA Chesapeake Bay Program Office

The analysis using the extended period followed the same procedure as previous analyses except that the data were extended back to 1930, only the weighted flow data based on multipliers were used, and the Log Pearson III method was used to determine the return period. Table G-8 lists the return periods for each of the monthly intervals for the extended period, with return periods greater than 6 years highlighted.

Table G-8. Extended period (1930–2009) return periods

% DO Exceedences	24.97%	25.87%	25.92%	24.26%	22.58%	27.84%	31.11%	27.24%
Year	1991-1993	1992-1994	1993-1995	1994-1996	1995-1997	1996-1998	2003-2005	2004-2006
jan-july	2.69	11.80	8.95	8.72	1.77	16.28	11.76	4.37
jan-june	3.05	13.72	9.84	8.14	1.69	17.59	9.71	3.03
jan-may	4.61	24.98	19.13	10.56	1.69	25.43	7.20	2.73
jan-apr	7.48	39.45	34.34	10.82	1.81	16.67	7.48	3.59
jan-mar	2.18	3.24	4.32	13.91	4.28	46.60	5.51	4.33
dec-july	3.03	9.20	9.15	7.92	2.69	15.66	20.18	9.88
dec-june	3.35	9.90	9.98	7.52	2.62	17.02	19.14	7.95
dec-may	4.76	16.77	17.73	9.20	2.76	23.09	16.70	8.14
dec-apr	6.96	20.14	23.89	9.10	3.01	16.01	16.48	9.99
dec-mar	2.68	3.49	5.42	9.87	7.27	31.16	13.94	13.66
nov-july	1.66	2.08	3.29	2.63	3.11	2.75	1.35	1.31
nov-june	3.39	8.92	9.67	7.10	3.18	20.60	25.44	10.69
nov-may	4.68	13.11	15.60	8.48	3.43	28.01	21.32	11.48
nov-apr	6.51	16.24	19.83	8.46	3.78	19.26	21.02	15.07
nov-mar	2.84	3.43	5.51	8.90	8.28	34.04	17.98	17.83
oct-july	3.64	6.50	7.38	6.27	3.71	18.35	32.07	18.23
oct-june	4.12	6.98	8.03	5.91	3.72	19.90	31.72	15.37
oct-may	5.69	9.02	10.95	7.06	4.09	25.80	26.88	16.45
oct-apr	7.66	10.82	14.96	7.08	4.40	18.91	26.38	19.62
oct-mar	3.42	2.92	4.50	7.25	8.82	29.23	20.77	22.25
sep-july	3.39	5.40	6.73	5.06	4.18	17.56	69.44	38.08
sep-june	3.86	5.81	7.27	4.87	4.26	18.29	62.21	30.68
sep-may	4.93	7.51	9.31	5.64	4.62	21.90	56.34	34.77
sep-apr	6.60	8.70	11.93	5.68	4.90	17.28	52.38	40.22
sep-mar	3.25	2.74	4.31	5.78	9.16	23.34	40.15	43.20

The monthly intervals with high correlations with DO exceedances are September – June, November–June, December–June, September–July, and December–July. Table G-9 highlights the return periods for the monthly intervals with high correlations with DO exceedances.

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Table G-9. Return periods for monthly intervals highly correlated to Chesapeake Bay DO criteria exceedances

Interval	1992–1994	1993–1995	1994–1996	1996–1998
September–June	5.81	7.27	4.87	18.29
November–June	8.92	9.67	7.10	20.60
December–June	9.90	9.98	7.52	17.02
September – July	5.40	6.73	5.06	17.56
December – July	9.20	9.15	7.92	15.66

Analysis of Critical Period using De-Trended Flow Data

As previously noted, initial analysis of the 3-year average flows from 1978 through 2009 did not reveal any 3-year periods before 1992 with return periods greater than 6 years for the monthly intervals included in the analysis. This indicates a potential increasing trend in flow volume over the last several decades. De-trending removes any flow trends over time and allows for an equal comparison of current and historic flows. It can remove the effects of urbanization and other impacts, which are apparent in the flow data.

The first step in de-trending was to determine if there is a significant trend in the flow data. The slope of the trend line is 0.1878. The Kendall Tau ranking correlation coefficient was used to determine if this is a statistically significant trend. The Tau value can range between –1 and 1, with a positive number indicating an increasing trend and a negative number indicating a decreasing trend. The flow data from 1930 through 2009 had a positive Tau value. A p-value < 0.05 indicates a statistically significant trend. The time-series flow data had a p-value of 0.0042, which is statistically significant. Figure G-3 shows the trend line in the raw data.

After establishing that a statistically significant increasing trend exists in the flow data, a de-trended time-series was developed. Two different methods were used to fit a trend line through the time-series data—Linear Least Squares Regression, and the Locally Weighted Scatter Plot Smoothing (LOWESS) (Helsel and Hirsch 2002; NIST and SEMATECH 2006).

The linear regression trend line was estimated by fitting the time-series data using a trend line of the form $y = mx + c$ (where m is the slope, c is the intercept, y being the dependent variable, i.e., flow, and x the independent variable time). The LOWESS fit is determined by specifying a smoothening parameter, which defines the subset of data that will be used for the local fit. The LOESS technique performs a weighted least square regression fit (on a subset of points) in a moving range around the x value (time), where the values in the moving range are weighted according to their distance from this x value. For that analysis, a smoothening parameter of 0.33 was found to fit the data trend reasonably well. Details of the LOWESS computation are at: http://www.itl.nist.gov/div898/handbook/pmd/section1/dep/dep144.htm.

The residuals were then calculated for each method (i.e., the difference between the observed and predicted values along the trend line). Finally, the residuals were added to the last point in the time series (the maximum value) to generate a de-trended time series. To confirm that no trend exists in the resulting de-trended time series using the linear regression approach, the linear slope was calculated. The slope was zero, indicating that there was no remaining trend. For the

de-trended time-series using the LOWESS regression, the presence of no trend in the time-series was confirmed using a p-value. The p-value of the de-trended data was 1.2376, indicating a statistically insignificant trend (p-value < 0.05 is significant). Figure G-4 plots the de-trended data.
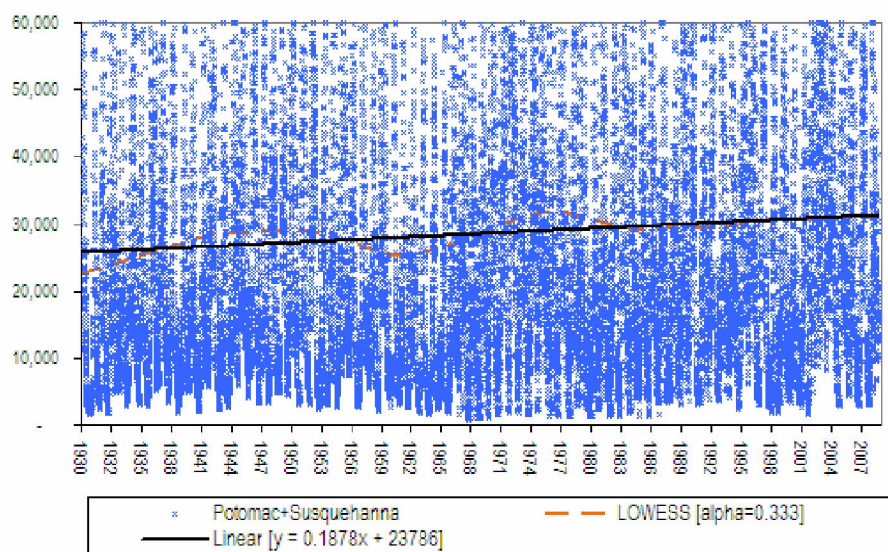

Figure G-3. Raw flow data with trend line.
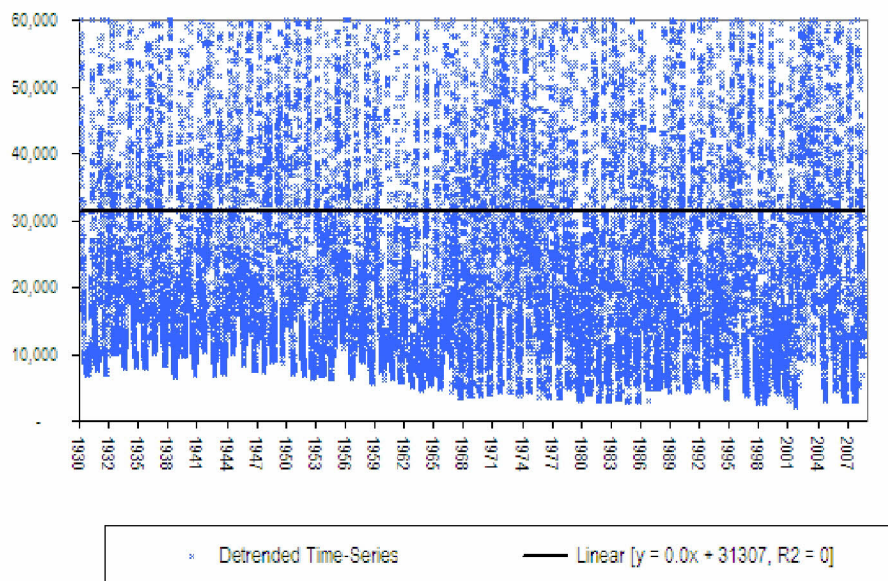
Figure G-4. De-trended data with slope of zero.

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Linear Regression to Determine Return Period

Using the linear regression de-trended data yielded revised return periods, which are in Table G-10. Table G-11 highlights return periods for the monthly spans with the highest correlation to DO exceedances.

Table G-10. De-trending analysis results using linear regression

% DO Exceedences	25.87%	25.92%	24.26%	22.58%	27.84%	31.11%	27.24%
Year	1992-1994	1993-1995	1994-1996	1995-1997	1996-1998	2003-2005	2004-2006
jan-july	7.53	5.51	5.14	1.41	9.02	6.05	2.49
jan-june	8.57	6.62	4.89	1.39	9.82	5.28	1.97
jan-may	16.31	11.91	6.84	1.41	15.37	3.88	1.85
jan-apr	26.99	22.35	7.73	1.54	10.27	4.50	2.46
jan-mar	2.67	3.36	9.85	3.28	34.34	3.92	3.10
dec-july	6.52	6.34	4.95	1.95	9.54	11.75	5.74
dec-june	7.38	7.36	4.83	1.95	10.73	11.13	4.48
dec-may	11.05	11.80	6.33	2.06	15.37	9.18	4.57
dec-apr	16.93	19.29	6.92	2.28	11.43	10.39	6.93
dec-mar	2.83	4.30	8.35	5.44	26.43	9.67	9.45
nov-july	2.80	4.80	3.61	4.36	3.69	1.46	1.41
nov-june	6.35	7.03	4.60	2.29	14.35	15.47	6.38
nov-may	9.00	10.18	5.63	2.44	19.11	13.24	6.80
nov-apr	12.56	16.41	6.16	2.77	15.06	14.98	9.32
nov-mar	2.75	4.30	7.17	6.40	29.15	13.42	13.06
oct-july	4.31	4.71	4.05	2.48	12.57	19.18	9.92
oct-june	4.64	5.26	3.96	2.58	13.94	18.36	8.54
oct-may	6.42	7.83	4.53	2.79	18.18	16.63	9.13
oct-apr	8.37	10.70	4.77	3.12	14.50	18.16	13.31
oct-mar	2.29	3.42	5.25	6.88	23.92	15.97	16.78
sep-july	3.75	4.39	3.45	2.81	11.30	40.03	21.57
sep-june	4.00	4.73	3.31	2.87	13.01	42.41	18.94
sep-may	4.91	6.67	3.79	3.13	16.03	37.44	20.99
sep-apr	6.53	8.84	4.01	3.48	12.77	39.63	29.60
sep-mar	2.14	3.23	4.29	7.21	19.30	32.86	34.85

Table G-11. Return periods for monthly intervals highly correlated to Chesapeake Bay DO criteria exceedances using linear regression de-trended flow data.

Interval	1992–1994	1993–1995	1994–1996	1996–1998
September–June	4.00	4.73	3.31	13.01
November–June	6.35	7.03	4.60	14.35
December–June	7.38	7.36	4.83	10.73
September–July	3.75	4.39	3.45	11.30
December–July	6.52	6.34	4.95	9.54

LOWESS Polynomial Regression

Using LOWESS regression to de-trend the data, the 3-year return periods were recalculated (Tables G-12 and G-13).

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Table G-12. De-trending analysis results using LOWESS polynomial regression

% DO Exceedences	24.97%	25.87%	25.92%	24.26%	22.58%	27.84%	31.11%	27.24%
Year	1991-1993	1992-1994	1993-1995	1994-1996	1995-1997	1996-1998	2003-2005	2004-2006
jan-july	2.25	11.24	8.10	7.33	1.42	11.81	7.30	2.60
jan-june	2.57	13.21	9.07	6.67	1.40	13.47	6.26	1.98
jan-may	3.88	23.61	17.29	8.59	1.44	18.30	4.16	1.88
jan-apr	6.54	38.98	32.42	9.11	1.58	12.20	4.73	2.53
jan-mar	1.98	3.00	3.95	13.24	3.61	44.48	4.14	3.21
dec-july	2.61	9.21	8.92	7.01	2.06	12.92	15.91	7.02
dec-june	2.99	9.92	9.82	6.55	2.05	14.52	14.78	4.95
dec-may	4.23	17.41	18.11	8.19	2.15	19.58	11.04	4.92
dec-apr	6.39	21.35	25.19	8.30	2.44	13.25	12.00	7.63
dec-mar	2.39	3.18	4.99	9.93	6.51	35.53	11.54	11.12
nov-july	1.73	2.15	3.58	2.65	3.13	2.67	1.30	1.31
nov-june	3.02	8.93	9.61	6.16	2.47	18.92	19.92	7.68
nov-may	4.13	14.14	16.91	7.59	2.62	28.85	17.34	7.96
nov-apr	5.91	17.53	22.63	7.72	3.00	17.97	17.60	10.73
nov-mar	2.47	3.08	4.99	8.85	7.67	44.25	16.87	16.58
oct-july	3.16	6.30	7.20	5.28	2.81	18.23	31.63	14.98
oct-june	3.63	6.83	7.95	4.91	2.85	20.09	30.32	11.10
oct-may	4.95	9.06	11.49	5.97	3.06	28.12	23.30	11.96
oct-apr	7.36	11.36	16.16	6.17	3.45	17.97	22.69	16.49
oct-mar	3.10	2.57	4.14	6.83	8.28	33.96	19.30	20.54
sep-july	3.00	4.97	6.38	4.44	3.18	16.66	81.73	36.71
sep-june	3.32	5.35	7.02	4.21	3.24	18.26	82.60	29.70
sep-may	4.46	7.18	9.27	4.63	3.51	22.56	73.13	34.38
sep-apr	6.09	8.59	12.46	4.76	4.01	16.11	59.30	40.07
sep-mar	2.92	2.37	3.87	5.01	8.65	25.51	44.82	48.49

Table G-13. Return periods for monthly intervals highly correlated to Chesapeake Bay DO criteria exceedances using LOWESS polynomial regression de-trended flow data

Interval	1992–1994	1993–1995	1994–1996	1996–1998
September–June	5.35	7.02	4.21	18.26
November–June	8.93	9.61	6.16	18.92
December–June	9.92	9.82	6.55	14.52
September–July	4.97	6.38	4.44	16.66
December–July	9.21	8.92	7.01	12.92

Summary of Analyses

No strict guidance exists on determining the critical period; however, the general approach is to determine the critical period for TMDLs on the basis of data availability, capturing the worst conditions in the period of record, capturing a range of flows, or 7Q10 flow. The availability of many decades of flow and water quality monitoring data in the Chesapeake Bay watershed allowed the opportunity to select a critical period from a group of candidate periods, so there is some freedom to follow a very rational approach to the selection of the period. It is EPA's best professional judgment that a 10-year return period captures a good balance between guarding against extreme events and ensuring attainment during more frequent critical events.

The analyses presented here take into account two methods of calculating probability, two methods of giving weight to more effective basins, two periods to calculate long-term probability, and two de-trending methods. All methods are more or less relevant and are considered as a group to determine the critical period most indicative of a 10-year return period. Of the candidate periods, 1996–1998 and 1993–1995 are closest to the 10-year return period. Table G-14 below summarizes the results from the two candidate periods.

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Table G-14. Summary of results for 1993–1995 and 1996–1998 periods

	All tributaries (1978–2009)		Potomac + Susquehanna (1930–2009)		
	Without multiplier	With multiplier	With multiplier	With multiplier	With multiplier
	No de-trending	No de-trending	No De-trending	De-trended (Linear regression)	De-trended (LOWESS)
Year			1993–1995		
Median (High r²)	7.53	7.48	7.27	6.34	8.92
Mean (High r²)	6.84	6.99	7.39	5.97	8.35
Median (All monthly spans)			9.31	6.62	9.07
Mean (All monthly spans)			11.28	8.05	11.26
Overall range 1993–1995	**5.97–11.28**				
Year			1996-1998		
Median (High r²)	18.95	16.02	17.56	11.3	16.66
Mean (High r²)	18.82	14.87	15.24	11.78	16.26
Median (All monthly spans)			19.26	14.35	18.26
Mean (All monthly spans)			21.63	15.57	21.05
Overall range 1996–1998	**11.30–21.63**				

Using the above table to compare 1993–1995 and 1996–1998, it is clear that in all methods of determining the return period, the 1996–1998 period has a return period of greater than 10 years. The period 1993–1995 is generally evaluated to be slightly below a 10-year return period, but the overall range incorporates the 10-year period. The Water Quality Goal Implementation Team selected 1993–1995 as the most appropriate critical period for assessment of the jurisdictions' DO water quality standards because it was the most consistent with existing Chesapeake Bay watershed jurisdictions' practices.

Critical Period for Water Clarity/SAV Standards Assessment

SAV responds negatively to the same suite of environmental factors that result in low to no DO conditions—high-flow periods yielding elevated loads of nitrogen, phosphorus, and sediments (Dennison et al. 1993; Kemp 2004). High levels of nitrogen and phosphorus within the estuarine water column results in high level of algae, which block sunlight from reaching the SAV leaves. The same high concentrations of nitrogen and phosphorus also fuel the growth of epiphytes or microscopic plants on the surface of the SAV leaves, also directly blocking sunlight. Sediment in the form of total suspended solids further reduces that amount of sunlight reaching the SAV leaves. Therefore, the critical period of 1993–1995 that was selected for assessing the jurisdictions' DO water quality standards was also selected as the same critical period for assessing the water clarity/SAV water quality standards.

Critical Period for Chlorophyll a Standards Assessment

Algae, measured as chlorophyll *a*, responds to a multitude of different environmental factors, parameters, and conditions including the following:

- Nitrogen and phosphorus loads
- Water column temperature

- pH conditions

- Local nutrient conditions (e.g., fluxes of nutrients from the bottom sediments)

- River flow influences on dilution of existing algae populations

- River flow, bathymetry, and other factors influencing residence time

- Local weather conditions (e.g., wind, percentage of sunlight)

- Other conditions and parameters not well understood in the current state of the science

Some of those same factors influence DO conditions, while others are unique to algae. As documented below, by applying the same methodology used to determine the critical period for DO (and water clarity/SAV) water quality standards assessment, a specific 3-year critical period appropriate for assessing the chlorophyll *a* water quality standards was not supported by the analyses.

Using the same methodology as was used to determine the DO critical period for the entire Chesapeake Bay, a flow analysis was conducted to support the selection of a critical period for the James River on the basis of the correlation between flow and chlorophyll *a* violations.

Flow from USGS Gage 02037500 – James River near Richmond, Virginia, was analyzed for the period 1935–2009. De-trending was unnecessary because no trend was detected from the flow time series. The average annual flows and running 3-year average flows were calculated for the James River. The 3-year averages were used to determine the corresponding exceedance probabilities and return period for the flows. The exceedance probability was determined using both the Weibull Plotting Position and the Log Pearson III Method. The return period is defined as the inverse of the exceedance probability. Table G-15 summarizes the flow and return period using both the Weibull Plotting Position and Log Pearson III Method. Although the analysis includes all years between 1935 and 2009, only the years 1985 through 2006 are shown below, because those are the years with available data on water quality criteria violations.

To determine whether a correlation exists between 3-year mean annual flows and the percent violations for chlorophyll *a*, two methods were used: the R-squared value and Kendall's Tau. Chlorophyll *a* violations were tested for both the spring and summer by individual segments and for the James River as a whole for the years 1985–2006. Table G-16 summarizes the results of the analyses. Generally, a strong correlation does not exist between the percent chlorophyll *a* violations and the 3-year average flow. The two exceptions were JMSTFL – Spring and JMSTFU – Summer, which had statistically significant correlations but were shown to have an inverse relationship between flow and chlorophyll *a* violations. Because the James River did not exhibit a correlation between high flow and chlorophyll *a* violations, a critical period was not selected on the basis of those factors..

Within the selected 1991-2000 hydrologic period, the return periods for the three year assessment periods were generally four years or less for the James River, well below the 10-year return frequency selected by the Water Quality Goal Implementation Team (Table G-15). The exceptions were 1994-1996 with about an 8 year return period and 1996-1998 with a 15 year return period. These return periods were derived using both the the Weibull Plotting Position and the Log Pearson III Method. This evaluation of return periods also did not support selection of a critical period for the James River.

Table G-15. James River 3-year flow averages and return period

Assessment Period	James River flow (cfs)	Flow rank	Weibull return period (yr)	Log Pearson III return period (yr)
1985-1987	7,057	36	2.08	2.37
1986-1988	5,780	53	1.42	1.36
1987-1989	7,386	28	2.68	2.88
1988-1990	7,073	35	2.14	2.39
1989-1991	8,018	19	3.95	4.36
1990-1992	7,270	30	2.50	2.67
1991-1993	7,502	25	3.00	3.08
1992-1994	8,011	21	3.57	4.34
1993-1995	8,012	20	3.75	4.34
1994-1996	8,836	10	7.50	8.24
1995-1997	8,225	17	4.41	4.93
1996-1998	9,526	5	15.00	14.56
1997-1999	7,211	31	2.42	2.57
1998-2000	6,645	41	1.83	1.92
1999-2001	4,240	72	1.04	1.03
2000-2002	3,975	74	1.01	1.02
2001-2003	7,277	29	2.59	2.69
2002-2004	9,235	7	10.71	10.99
2003-2005	10,320	3	25.00	30.50
2004-2006	7,701	22	3.41	3.48

Because a specific 3-year critical period appropriate for assessment of the chlorophyll a water quality standards in the tidal James River was not supported by these analyses—e.g., no critical period was selected—EPA determined the need to evaluate all eight 3-year periods in the 1991–2000 hydrologic period to assess attainment of the chlorophyll a water quality standards in the tidal James River.

Table G-16. Correlation analyses for flow and chlorophyll a violations

Segment	p-value	Kendall Tau	Level of significance	R^2
Spring-Whole James	0.4180	– 0.14	> 0.01	0.008
Summer-Whole James	0.4966	– 0.12	> 0.01	0.061
Spring-JMSMH	0.7188	0.06	> 0.01	0.029
Spring-JMSOH	0.0250	– 0.37	>0.01	0.274
Spring-JMSPH	0.9204	0.02	>0.01	0.084
Spring-JMSTFL	**0.0058**	**– 0.45**	**<0.01**	**0.519**
Spring-JMSTFU	0.1616	– 0.23	>0.01	0.117
Summer-JMSMH	0.6242	0.08	>0.01	0.027
Summer-JMSOH	0.5824	0.09	>0.01	0.004
Summer-JMSPH	0.6242	0.08	>0.01	0.015
Summer-JMSTFL	0.0644	– 0.31	>0.01	0.219
Summer-JMSTFU	**0.0001**	**– 0.63**	**<0.01**	**0.519**

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References

ADEM (Alabama Department of Environmental Management). 1996. *TMDL Bayou Sara/Norton Creek – Mobile River Basin Organic Enrichment/DO*. Alabama Department of Environmental Management, Montgomery, AL.

ADEM (Alabama Department of Environmental Management). 2005. *Organic Enrichment/Dissolved Oxygen TMDL Rabbit Creek and Dog River*. Alabama Department of Environmental Management, Montgomery, AL.

ADEM (Alabama Department of Environmental Management). 2006. *Total Maximum Daily Load Organic Enrichment/Dissolved Oxygen Threemile Creek, Alabama*. Alabama Department of Environmental Management, Montgomery AL.

Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation habitat requirements as barometers of Chesapeake Bay health. *Bioscience* 43:86–94.

DNREC (Delaware Department of Natural Resources and Environmental Control). 1998. *Total Maximum Daily Load Analysis for Indian River, Indian River Bay and Rehoboth Bay, Delaware*. Delaware Department of Natural Resources and Environmental Control, Dover, DE.

DNREC (Delaware Department of Natural Resources and Environmental Control). 1998. *Total Maximum Daily Load Analysis for Nanticoke River and Broad Creek, Delaware*. Delaware Department of Natural Resources and Environmental Control, Dover, DE.

DNREC (Delaware Department of Natural Resources and Environmental Control). 2004. *TMDLs for The Little Assawoman Bay and Tributaries and Ponds of the Indian River, Indian River Bay, and Rehoboth Bay*. Prepared by ENTRIX, Inc., New Castle, DE, and J.E. Edinger Associates, Inc., Wayne, PA.

Helsel, D.R., and R.M. Hirsch. 2002. *Techniques of Water-Resources Investigations of the United States Geological Survey*. Chapter A3: Statistical methods in water resources. Book 4, Hydrologic Analysis and Interpretation.

Kemp, W.M., R.A. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, C.L. Gallegos, W. Hunley, L. Karrh, E. Koch, J.M. Landwehr, K.A. Moore, L. Murray, M. Naylor, N.B. Rybicki, J.C. Stevenson, and D.J. Wilcox. 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime and physical-chemical factors. *Estuaries* 27:363–377.

Malcolm Pirnie, Inc. 2009. *Technical Memorandum: Analysis of January-May Inflows to the Chesapeake Bay During the 1996-98 Period*. Malcolm Pirnie, Inc., Newport News, VA.

MassDEP and USEPA (Massachusetts Department of Environmental Protection and U.S. Environmental Protection Agency, New England Region). 2007. *TMDL for Nutrients in the Lower Charles River Basin, Massachusetts*. Massachusetts Department of Environmental

Protection, Worcester, MA, and U.S. Environmental Protection Agency, New England Region Boston, MA.

MDE (Maryland Department of the Environment). 2006. *Total Maximum Daily Loads of Nitrogen and Phosphorus for Baltimore Harbor in Anne Arundel, Baltimore, Carroll, and Howard Counties and Baltimore City, Maryland.* Maryland Department of the Environment, Baltimore, MD.

MDE (Maryland Department of the Environment). 2006. *Total Maximum Daily Loads of Nitrogen and Phosphorus for the Upper and Middle Chester River, Kent and Queen Anne's Counties, Maryland.* Maryland Department of the Environment, Baltimore, MD.

MDE and DC DOE (Maryland Department of the Environment and District of Columbia Department of the Environment). 2008. *Total Maximum Daily Loads of Nutrients/Biochemical Oxygen Demand for the Anacostia River Basin, Montgomery and Prince George's Counties, Maryland and The District of Columbia.* Maryland Department of the Environment, Baltimore, MD, and District of Columbia Department of the Environment, Washington, DC.

NIST (National Institute of Standards and Technology) and SEMATECH. 2006. *e-Handbook of Statistical Methods.* U.S. Commerce Department's Technology Administration. <http://www.itl.nist.gov/div898/handbook/>.Updated: 7/18/2006.

NYSDEC (New York State Department of Environmental Conservation) and CTDEP (Connecticut Department of Environmental Protection). 2000. *A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound.* New York State Department of Environmental Conservation, Albany, NY, and Connecticut Department of Environmental Protection, Hartford, CT.

Peconic Estuary Program. 2007. *Total Maximum Daily Load for Nitrogen in the Peconic Estuary Program Study Area Including Waterbodies Currently Impaired Due to Low Dissolved Oxygen: The Lower Peconic River and Tidal Tributaries; Western Flanders Bay and Lower Sawmill Creek; and Meetinghouse Creek, Terrys Creek and Tributaries.* Peconic Estuary Program, Yaphank, NY.

Ponce, V.M. 1989. *Engineering Hydrology: Principles and Practices.* Prentice-Hall, Inc., New York, NY.

SCDHEC (South Carolina Department of Health and Environmental Control). 2002. *Total Maximum Daily Load Cooper River, Wando River, Charleston Harbor System, South Carolina.* South Carolina Department of Health and Environmental Control, Charleston, SC.

SCDHEC (South Carolina Department of Health and Environmental Control). 2003. Total Maximum Daily Load Ashley River, South Carolina. South Carolina Department of Health and Environmental Control, Charleston, SC.

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VADEQ (Virginia Department of Environmental Quality). 2009. Total Maximum Daily Load for Dissolved Oxygen in Mill Creek, Northampton County, Virginia. Prepared by Virginia Institute of Marine Science, Gloucester Point, VA.

USEPA (U.S. Environmental Protection Agency). 2003. *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*. EPA 903-R-03-002. U.S. Environmental Protection Agency, Region 3, Chesapeake Bay Program Office, Annapolis, MD.

U.S. Interagency Advisory Committee on Water Data. 1982. *Guidelines for determining flood-flow frequency*. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Va., 183 p., <http://water.usgs.gov/osw/bulletin17b/bulletin_17B.html>.

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